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**Synaesthetes show advantages in savant skill acquisition:**

**Training calendar calculation in sequence-space synaesthesia**

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**Abstract**

Previous research has suggested that synaesthetic experiences may create the foundation for superior skills to emerge of the type found in savant syndrome (e.g., Simner, Mayo, & Spiller, 2009). People with sequence-space synaesthesia experience units of time (e.g., days, months, years) as a pattern in space, either within the mind's eye or as a 3d projection outside of the body. Our study investigates whether sequence-space synaesthesia facilitates the learning of the savant skill known as 'calendar calculation' where an individual can give the correct day of the week for any given date (e.g., 18th September 1990 was a Tuesday). Using a novel experimental methodology, we trained a group of sequence-space synaesthetes as well as non-synaesthete controls how to calendar calculate over two weeks with a final calendar calculation test in the third week. We show for the first time that calendar calculation is relatively easy to acquire: following training sessions totalling one hour participants could select a day, from a set of several thousand, within ~10 seconds and with ~80% accuracy. Synaesthetes were not found to have improved abilities from the start, but they outperformed controls in our final calendar calculation test. We suggest that sequence-space synaesthesia may have provided an advantage in performing calendar calculation after the opportunity for initial learning had taken place. This supports the notion of synaesthesia as a foundation for superior, and perhaps sometimes savant-like, skills.

Keywords: sequence space synaesthesia, calendar calculation, savant syndrome

## Introduction

*Synaesthesia* produces sensory experiences that are evoked by stimuli in unusual ways (e.g., Simner, 2012). For instance, people with *grapheme-colour synaesthesia* report that graphemes (letters or numbers) induce sensations of colour (Simner, Glover, & Mowat, 2006) while people with *music-colour synaesthesia* report the experience of colour in response to music (Ward, Huckstep, & Tsakanikos, 2006). The current study focuses on *sequence-space synaesthesia* where linguistic sequences such as numbers, years, months, and days of the week are experienced as a pattern in space, either within the mind's eye or as a visualised 3d projection outside of the body (Simner, 2012). These patterns are imagined spatial arrays, where each unit in the sequence (e.g., each number) appears to the synaesthete to have a 'natural place'. The spatial patterns vary from synaesthete to synaesthete -- for example, months can be arranged in ovular, horizontal, vertical, or other idiosyncratic forms (Figure 1). The arrays are consistent over time and experienced automatically (Smilek, Callejas, Dixon, & Merikle, 2007; but see Price & Mattingley, 2013). This study examines the extent to which these mental images of time can be used as a scaffold to aid the learning of a skill known as calendar calculation – which is the ability to name the day of the week for a given date (e.g., 18$^{th}$ September 1990 was a Tuesday).

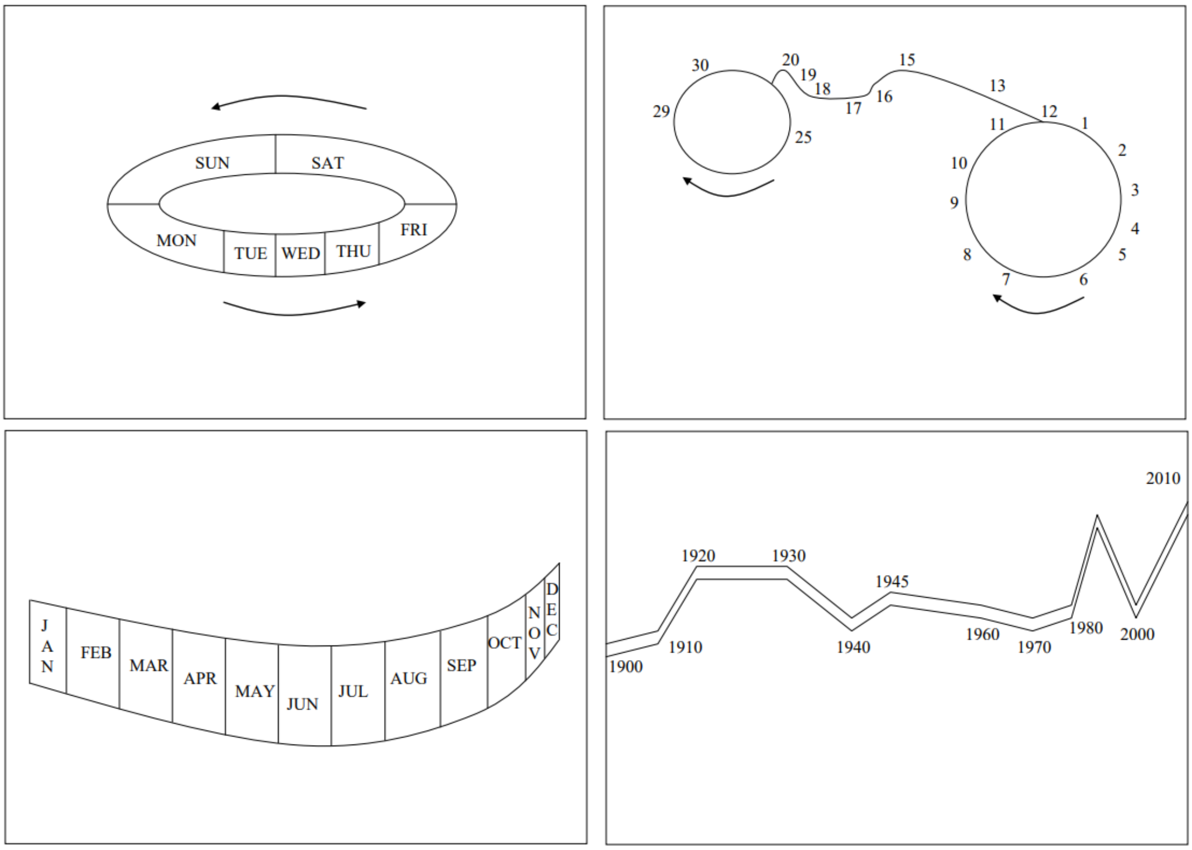


Figure 1: Examples of four different synaesthetes' self-reported spatial forms representing the days of the week (top-left), days of the month (top-right), months (bottom-left), and years (bottom-right). These synaesthetes were first described in Simner, Mayo, & Spiller (2009) and they drew their spatial forms, which we represent here.

Calendar calculation is a skill that can be learned by any person willing to internalise a set of relatively complex calendar-based rules, but it is a skill particularly associated with *prodigious savant syndrome* (henceforth 'savant syndrome'; Treffert, 2014). In savant syndrome, individuals display one or more specialised talents in addition to having a developmental condition such as autism spectrum conditions (ASC; Miller, 1999). The remarkable nature of savant syndrome comes from the fact that the talents observed in such individuals far exceed not only their own level of developmental functioning, but that of most people in the general population. Savant skills can exist in a variety of areas including skills in art (e.g., the ability to draw hyper-detailed cityscapes from memory), music (high proficiency in musical instrument playing), maths (lightening mental arithmetic), memory recall (of numbers, facts, events), and indeed calendar calculation (the ability to provide the day of the week for a given date; Treffert, 2014). In the current paper we look at the savant skill of calendar calculation to determine whether it might be linked to, or facilitated by, sequence-space synaesthesia. The motivation for testing the relationship between sequence-space synaesthesia and calendar calculation comes from several previous strands of research. These converge on the hypothesis that savant skills such as calendar calculation might be especially likely in ASC individuals with synaesthesia. Not only does synaesthesia provide a number of cognitive abilities likely to be relevant to calendar calculation, but synaesthesia and savant syndrome have been directly tied in epidemiological studies (albeit without a focus on calendar calculation in particular). We review this evidence briefly below and then describe our proposed study.

The precise skills that underpin calendar calculation are largely unknown, but brain imaging studies suggest that calendar calculation involves mental arithmetic (Minati & Sigala, 2013). An fMRI study of two savants showed that calendar calculation and arithmetic tasks shared overlapping activations in bilateral parietal lobe (Cowan and Frith, 2009), in a similar region to when mental arithmetic is performed by typical individuals (Menon, Rivera, White, Glover, & Reiss, 2000). However, some savants may utilise approaches beyond arithmetic and, as explained later, the arithmetic need not be more complex than ‘counting on’ (e.g., adding or subtracting 3 days to Monday). Mottron, Lemmens, Gagnon, and Seron (2006) found that the calendar calculating savant DBC could answer specifically prepared ‘reversed’ questions (e.g., *Which day was the second Friday of September 1992?*) that could not be answered based on classical calendar algorithms. In addition, Fehr, Wallace, Erhard, and

Herrmann (2011) found a more distributed network of fMRI activation for an individual with savant syndrome during a calendar calculation task, beyond regions linked to pure arithmetic alone. All this suggests that while calendar-calculating savants might use rules and mental arithmetic to some extent, they may also rely on other skills. And some of these – we argue – might be especially salient in synaesthesia.

In addition to mental arithmetic, calendar calculation is likely to rely on rote memorisation of calendar-related knowledge stored in long-term memory (e.g., the repetitive and internal structure of different years; Boddaert et al., 2005; Heavey, Pring, & Hermelin, 1999). It is interesting to note therefore that enhanced memory is a feature specifically associated with synaesthesia (e.g., Radvansky, Gibson, & McNerney, 2011; Rothen, Meier, & Ward, 2012; Yaro & Ward, 2007) and that sequence-space synaesthetes in particular have superior skills in manipulating calendar-related knowledge. In two studies they performed better than controls in naming every third month in reverse-chronological order (Mann, Korzenko, Carriere, and Dixon, 2009) and in dating the years of famous international events (Simner, Mayo and Spiller, 2009). Another skill tied to both synaesthesia and calendar calculation is enhanced mental imagery. Roberts (1945) suggested that calendar calculation skills might be based to some extent on visual imagery, and a number of studies have suggested heightened imagery as a feature of synaesthesia -- especially sequence-space synaesthesia (Havlik, Carmichael, & Simner, 2015; Mealor, Simner, Rothen, Carmichael, & Ward, 2016; Price & Mattingley, 2013; Price & Pearson, 2013; Rizza & Price, 2012). There is also some evidence that the *type* of imagery in sequence-space synaesthesia might be particularly aligned to those of savant calendar calculators. Howe and Smith (1988) describe a 14-year-old savant, Dave, with calendar calculation skills who describes relying on "stored visual images of calendar months" (p.381) and had an obsession with the "physical form of the calendar months" (p.381). These “stored visual images of calendar months” appears to be a description of sequence-space synaesthesia. In other words, the specific synaesthetic visualisations of time in sequence-space synaesthesia might be precisely those that facilitate calendar calculation.

In a number of ways then, sequence-space synaesthesia appears to carry some of the necessary or desirable skills which might conceivably aid in developing the savant skill of calendar calculation. One previous model has brought together synaesthesia and calendar calculation in an explicit way (Simner, Mayo, and Spiller, 2009; Baron-Cohen et al., 2007). This model suggests that when both ASC and synaesthesia happen to co-occur within any given individual, each condition provides a helpful component for savant skills to emerge. First, the savant skill is facilitated by the a priori cognitive advantages afforded through synaesthesia (e.g., memory advantages), and second, these skills become exceptionally heightened because ASC may give an obsessive urge to over-rehearse them (American Psychiatric Association, 2013; see also Bennett & Heaton, 2012; LePort et al., 2012). In other words, where synaesthesia brings enhanced abilities in those without ASC (i.e., enhanced but within the normal range of ability), it may bring *exceptional* abilities in those *with* ASC (i.e., beyond the neurotypical range). These exceptional abilities would be savant skills. This model has been tested in a number of ways but most notably, there is evidence that synaesthesia is found more commonly in savants than in controls from the general population, and indeed in those with ASC but no savant skill (Hughes, Simner, Baron-Cohen, Treffert, & Ward, 2017). In the current study we investigate whether the savant skill of calendar calculation might be linked to the condition of sequence-space synaesthesia, by teaching this skill to everyday (non-savant) sequence-space synaesthetes. If synaesthetes show advantages in acquiring the skill of calendar calculation, this could offer indirect convergent evidence that savants with calendar calculation may themselves be relying to some extent on sequence-space synaesthesia.

In summary, we have suggested that calendar calculation skills originate from multiple pathways including the use of mental arithmetic, rote memorisation of dates, and mental imagery, which may possibly be synaesthetic in nature. Here we aim to test directly whether sequence-space synaesthetes are a priori better at calendar-calculation, by teaching sequence-space synaesthetes to calendar calculate. We hypothesise that sequence-space synaesthetes might show mildly superior abilities in calendar calculation compared to controls, and that this, therefore, could be linked to *exceptional* abilities in a similar vein in savant individuals. In our study we will utilise a novel experimental method which teaches calendar calculation using a structured, rule-based approach. By asking participants about their use of different strategies as well as their cognitive style (see below) we also aim to adjudicate between different accounts for the development of calendar calculation skills.

**Experimental Investigation**

In our study, we test a group of sequence-space synaesthetes and non-synaesthete controls. We taught the skill of calendar-calculation and gave one tutorial per week for two weeks, then a final session of testing in week 3 to assess longer-term retention of the skill. Each tutorial taught new rules of calendrical regularities that would enable the calculation of dates between the years 2011-2017 (e.g., March and November share the same pattern of days of the week). Our tutorials had 'Spot Quizzes' at the start and/or end to ensure participants were consolidating their learning (see Methods), and there were further Spot Quizzes in our final (testing only) session in Week 3. Our Main Test was the end-of-study exam in Week 3 which covered all the learning materials. We also gathered further information after our Main Test with a Strategy Questionnaire to understand what approaches participants had taken to learning and in a pre-Session before our tutorials began, we gave an arithmetic test to ensure there were no a priori differences in maths ability prior to training. Finally we also gave a synaesthesia-test to verify the group-status of participants (controls vs. synaesthetes) and a Cognitive Styles questionnaire, to test whether there were any other group differences. Details of all rules and tests are given in our Methods (and are described in full as they appeared in our study in Supplementary Materials A, B, and C) and Figure 2 (see further below) shows the overall structure of our testing sessions.

We predict that synaesthetes will show superior scores compared to controls in the Main Test and/or improved learning across the Spot Quizzes in each of the three sessions. We also have an additional hypothesis related to one particular rule: the 'matching month rule' (see Methods and Supplementary Materials). This rule will allow us to see if participants are appropriately applying the instructed rules, because this rule makes some of our questions simpler than others. The 'matching month rule' states that certain months match in their structure (e.g., the day of the week for any date in March is the same as in November; see Table 1). We therefore created 'primed' questions in our tests, where two consecutive questions would have the same answer. If participants have internalised our rules, 'primed' questions should therefore be easier and faster to answer compared to 'unprimed questions' (where two consecutive questions have *different* answers). Examples of a primed and unprimed question are shown in Table 1. Since primed questions should be easier *irrespective of participant group* (since less cognitive effort is required to work them out), finding this pattern across all subjects will give us confidence that both groups are learning and attempting to apply the instructed rules.

Table 1. Example questions from our primed and unprimed conditions. Conditions are 'primed' with respect to the 'matching month rule' (see Methods) which tells participants that certain months (e.g., March and November) have matching structures, so should generate the same answer.

| **Previous question** | **Following question** | |
|---|---|---|
| | **Primed condition** | **Unprimed condition** |
| What weekday was… 8$^{th}$ March 2015? | What weekday was… 8$^{th}$ November 2015? | What weekday was… 8$^{th}$ July 2015? |
| Answer: Sunday | Answer: Sunday | Answer: Wednesday |

In summary, we predict that sequence-space synaesthetes will perform better than controls on our tests of calendar calculation, and that all participants will find 'primed' questions easier.

## Methodology

### *Participants*

A total of 35 participants (25 female; mean age = 32.94; range = 18-50; SD = 10.41) completed all sections of our study. As part of our testing protocol (see Procedure) participants were divided into two groups: sequence-space synaesthetes and controls. Hence our cohort of 35 participants comprised 13 individuals with sequence-space synaesthesia (9 female; mean age = 32.62; range = 18-45; SD = 8.13), and 22 controls (16 female; mean age = 33.14; range = 19-50; SD = 11.73). Independent-samples t-tests showed no significant differences between groups in age, $t(32.01) = -.16$, $p = .878$, or highest qualification, $t(33) = .75$, $p = .459$. In addition to the above participants, a further 59 participants started but did not reach the end of our study. Of these, 10 participants dropped-out between the pre-session and Tutorial 1 (i.e., none of these participants attempted calendar calculation; see Figure 2). A further 31 participants dropped-out between Tutorial 1 and Tutorial 2, and 18 participants dropped-out between Tutorial 2 and Tutorial 3 (i.e., these participants attempted calendar calculation and partial datasets were analysable). Overall our drop-out rate was high because our study required a considerable time investment. But we took care to ensure that participant drop-outs did not account for the effects observed in our results section (see *Results*).

Participants were recruited using a mixture of email advertisements and word of mouth. Our synaesthete participants were largely recruited from the Sussex Synaesthesia Database (SSD) which is a group of people who have self-declared synaesthesia who have indicated their interest in taking part in research. Synaesthetes reported spatial forms for days, months and numbers[1]. Participants were entered into a £50 prize draw for their participation and our study was approved through the Cross-Schools Science and Technology Research Ethics Committee at the University of Sussex.

*Materials and Procedure*

All participants received an email invitation which briefly explained the purpose of the study and contained a URL link. This link redirected them to a further information and consent page (hosted on Qualtrics which is an online platform for building and distributing surveys). This explained in more detail the purpose of the study and what would be involved (i.e., a four-part study where you will learn how to calculate the day of the week from a given date). After providing consent participants then began the study.

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[1] Our 13 synaesthetes were classified as synaesthetes based on self-reports but we were also able to verify synaesthesia objectively for eight of these participants. Our pattern of results remains entirely unchanged when considering all 13 synaesthetes, or including only the 8 objectively-verified synaesthetes (see *Results*). Our objective test is described in detail elsewhere (Rothen, Jünemann, Mealor, Burckhardt, & Ward, 2016; Ward et al., 2018). The computerised test presents days, months and digits (0-9) one by one, and requires participants to click on-screen to indicate where each would fall in his/her own idiosyncratic spatial array. Each item (e.g., September) is repeated three times in a fully randomised list and responses result in three xy coordinates per item (i.e., a triangle). Synaesthetes must show they are highly consistent in their spatial forms meaning that the area of their triangles averaged across all items must be <.203% of the monitor size (Ward et al., 2018)

*Composition and overview of all study sessions*

All aspects of this study were completed online and in a location of the participants choosing (e.g., their home). The study was composed of four main parts (see Figure 2): Pre-session in week 1 (10-25 minutes); Tutorial 1 in week 1 immediately after the Pre-session (35 minutes); Tutorial 2 in week 2 (35 minutes); and a Final Test Session in week 3 (30 minutes). All the calendar calculation training took place in Tutorials 1 and 2 (in weeks 1 & 2 respectively), while the final calendar calculation Main Test was presented in the Final Test Session in week 3.

| Pre-session week 1 | Tutorial 1 week 1 | Tutorial 2 week 2 | Final Session week 3 |
|---|---|---|---|
| Demographics | Spot Quiz (Rule 1) | Spot Quiz (Rule 1) | Spot Quiz (Rule 1) |
| Sussex cognitive-styles questionnaire | | Spot Quiz (Rules 2-6) | Spot Quiz (Rules 2-6) |
| Synaesthesia test | | | Main Test (Rules 1-6) |
| Arithmetic test | | | Strategy Questionnaire |

Figure 2. The overall structure of the calendar calculation study (composed of a pre-session, Tutorial 1, Tutorial 2, and a Final Session). Contained within each section are the individual rules and tests. Tests that are connected were repeated across weeks.

*Pre-session (week 1)*

The pre-session obtained demographic and questionnaire data from the participant. The demographic questionnaire elicited age, gender, and education. Participants then completed the Sussex Cognitive Styles Questionnaire (SCSQ, Mealor et al., 2016) which is a 60 item measure that assesses the general cognitive profile of an individual. Participants answered using a 5-point Likert scale (*Strongly disagree*, *Disagree*, *Neither agree nor disagree*, *Agree*, *Strongly Agree*) and each question is linked to one or more of six factors: *imagery ability*, *technical/spatial abilities*, *language and word forms, need for organisation*, *global bias*, and *systemizing*.

After the SCSQ, participants completed the test for sequence-space synaesthesia (testing specifically for sequences of days, months, and digits). The procedure and analysis of the synaesthesia test is described in Footnote[1] above. Following the synaesthesia test participants completed an arithmetic test which was the final stage of the pre-session. The arithmetic test was hosted on www.millisecond.com, using the Inquisit software which is an online platform for hosting experiments. The test presented 20 arithmetic sums on screen (e.g., 37 + 25) and the participant was required to work out the answer in their head as quickly as possible and type the correct answer using the keyboard. All questions consisted of double-digit addition as this is theorised to be a more accurate reflection of arithmetic competency as opposed to other mathematical operators such as multiplication which involves more rote learning (Dehaene, 2001). After the arithmetic test participants were then presented with a link to begin the first calendar calculation tutorial (Tutorial 1). Participants could take a break if they wished and if they did not begin Tutorial 1 immediately after the pre-session an automatic link was sent to the participants email address which they could then access at any time to begin Tutorial 1. Once participants accessed this link, the calendar calculation training began.

*Tutorials 1 and 2 – Calendar calculation training (weeks 1 & 2)*

Tutorials 1 and 2 were conducted online using Inquisit. Within each tutorial we explained a set of calendar calculation rules (see below) based on patterns of the calendar. Tutorial 1 focussed on dates in the year 2015 only and Tutorial 2 extended this to the calculation of dates between the years 2011-2017. After the presentation of each rule participants were given two minutes to memorise the material just covered (with instructions not to write down the material) which was then followed by a series of practice questions to familiarise them with the rules. To measure how well participants were learning calendar calculation we also presented Spot Quizzes which tested participants on their knowledge from each Tutorial (see below to see how each Spot Quiz appeared within each Tutorial). All questions followed a forced-choice question format with the correct answer being one of the seven days of the week. Participants were required to answer using the keys 1 – 7 on the keyboard and they were given feedback ("correct"; or what the correct answer should have been e.g., "Tuesday"). Below is a brief description of each rule we taught, and full details of how each rule was taught during the study can be found in the Supplementary Materials. Table 2 contains additional information about which rules were included in each Tutorial and how they fed into our calendar calculation tests. Practice materials were emailed to participants at the end of Tutorials 1 & 2 and at the start of Tutorial 2 participants were asked how many minutes per day they had spent practicing the rules since the end of the last Tutorial. The practice materials were the same as the materials that were displayed to participants during the experimental phase of the study and can be found in Supplementary Materials A and B (corresponding to Tutorials 1 & 2 respectively).

Table 2. Column 1 shows the individual rules taught during this study (and the Tutorial they were taught during). Column 2 shows the test that each rule fed into (and the Tutorial the test appeared in*). Column 3 shows the testing format, and Column 4 shows an example question. For a more in-depth description of each of the rules refer to the Supplementary Materials.

| **Rule (Tutorial)** | **Test (Tutorial)** | **Question type** | **Example question** |
|---|---|---|---|
| Matching Months (1) | Spot Quiz: matching-month priming test (1,2,3) | Forced choice Jan-Dec (correct answer required) | "What month begins on the same day as November?" |
| Follow-on Months (1) | Spot Quiz: cross-years test (2,3) | Forced choice Mon-Sun | "If the 4$^{th}$ March 2015 is a Wednesday, what day is 4$^{th}$ June 2015?" |
| 1-8-15-22-29 (1) | Spot Quiz: cross-years test (2,3) | Forced choice Mon-Sun | "If the 1$^{st}$ March 2015 is a Sunday, what day is 29$^{th}$ March 2015?" |
| Follow-on Year & leap years, March to December (2) | Spot Quiz: cross-years test (2,3) | Forced choice Mon-Sun | "If the 1$^{st}$ March 2015 is a Sunday, what day is 1$^{st}$ March 2016?" |
| Follow-on Year & leap years, January to February (2) | Spot Quiz: cross-years test (2,3) | Forced choice Mon-Sun | "If the 11$^{th}$ January 2015 is a Sunday, what day is 11$^{th}$ January 2014?" |
| Matching months & leap years (2) | Spot Quiz: cross-years test (2,3) | Forced choice Mon-Sun | "What day was 4$^{th}$ March 2012?" |

*All rules presented during Tutorial 1 are also expanded on during Tutorial 2.

*Tutorial 1 (week 1)*

Throughout all training sessions, participants were given an anchor date to memorise ($1^{st}$ March 2015=Sunday) which simplifies the calculation of other dates (see Supplementary Materials A). Tutorial 1 taught Rules 1-3 below, then presented a *Spot Quiz* based on Rule 1.

**Rule 1**: *the matching-month rule*. Some months always have the same structure as each other: e.g., March and November begin on the same day of the week. Participants were shown a 2015 calendar and asked to identify matching months (7 untimed questions). Participants with incorrect responses had to then select the correct answer to continue, to reinforce learning.

**Rule 2**: *the follow-on month rule*. Months can be ordered with respect to their pattern of days. For instance, if 1st March 2015 = Sunday then 1st June 2015 = Monday. Thus, June has a +1 relationship in days to March and this relationship always holds true. Participants were shown a 2015 calendar rearranged to show this new pattern (see Supplementary Materials A). Participants had two minutes to memorise this and were then asked 25 timed questions of the type "If the $4^{th}$ March 2015 = Wednesday, what day is $4^{th}$ June 2015?".

**Rule 3**: *the 1-8-15-22-29 rule*. In every month, the 1st, 8th, 15th, 22nd, and 29th all fall on the same day. For example, in January 2015 these dates are all on Thursday and in March 2015 they are all on Sunday. Participants were given 2 minutes to memorise a calendar with these dates highlighted and then saw 25 timed questions of the type "If the $1^{st}$ March 2015 is a Sunday, what day is $29^{th}$ March 2015?".

**Spot Quiz (Rule 1)**: *matching-month priming test*. This had 40 timed questions presented in pairs (10 'primed' pairs and 10 'unprimed' pairs; see Introduction). Questions were displayed for unlimited time.

*Tutorial 2 (week 2)*

Tutorial 2 began by recapping the rules from Tutorial 1 and repeating its *Spot Quiz (Rule 1)*, but with a new selection of dates. The following three new rules were then presented (see Supplementary Materials B for all training materials from Tutorial 2).

**Rule 4**: *the follow-on year rule with leap years, March-December*. In most years, the first day of each month moves one day forward (e.g., 1$^{st}$ March 2014=Saturday, 1$^{st}$ March 2015=Sunday). In leap years (e.g., 2012, 2016), an extra day is inserted (29th February). When this happens, the first day of each month (from March onwards) jumps ahead by two days instead of one. From this, if 1$^{st}$ March 2015 = Sunday then 1$^{st}$ March 2016 (leap year) = Tuesday (+2 days). Participants had two minutes to memorise the materials, with accompanying images. Then, participants were asked seven questions of the type "What day was 1st March in 2014?" covering years 2011 to 2017. Following this, participants were asked a further 20 questions of the type "If the 6th November 2013 is a Wednesday, what day is 6th November 2012?" covering the months March-December.

**Rule 5**: *the follow-on year rule with leap years, January-February*. January and February also obey the follow-on year rule but in a slightly different way to above. Whereas days in March to December 'leap' by +2 in years such as 2012 & 2016, days in January and February have to wait until the next year (e.g., 2013 and 2017) to 'leap' by +2. For example, if the 1st January 2015 = Thursday, then the 1st January 2016 = Friday (+1) and the 1st January 2017 = Sunday (+2 after the leap year has occurred). Participants were shown images to reinforce this rule and given 2 minutes to memorise the content, they were then asked 20 timed questions of the type "If 11th January 2015 is a Sunday, what day is 11th January 2014?" covering the months January and February.

**Rule 6**: *the matching-month rule with leap years*. Some matching months are disrupted by leap years; when leap years occur the months January and February now align with different months (see Supplementary Materials B). Participants were given two minutes to memorise the material with images and then asked 20 questions of the type "What day was 4$^{th}$ March 2012".

**Spot Quiz (Rules 2-6)**: *the cross-years test*. This had 40 timed questions involving the calculation of dates spanning the years 2011-2017 half of which corresponded to leap years, and half of which corresponded to the 1$^{st}$, 8$^{th}$, 15$^{th}$, 22$^{nd}$, 29$^{th}$ of the month. Questions were of the type "What day was 18th December 2016".

*Main Test (week 3)*

No new rules were presented and instead participants were simply required to complete a series of tests. This session began by repeating the Spot Quizzes from Tutorial 1 and Tutorial 2 (with new selections of dates) and then the final calendar calculation Main Test. The Main Test had 40 timed date questions randomly selected between the years 2011-2017 and questions were presented in the format: "What day was 7$^{th}$ April 2013". The Main Test was designed to measure participants' overall calendar calculation knowledge gained over the entire study. The Final Test Session was hosted on Syntoolkit which is an online platform for hosting experiments. As with Tutorial 2, participants were first asked how many minutes per day they had practiced the rules from the previous Tutorial over the last week.

*Strategy questionnaire (week 3)*

After the Main Test participants completed a Strategy Questionnaire. This contained two sections, asking about the participants' enjoyment of the study (Q7, Q8, Q9; see Supplementary Materials D) and what strategies they used when calculating days of the week

(Q1, Q2, Q3, Q4; relating respectively to: picturing a mental calendar; using the on-screen timeline Mon, Tues, Wed…; using mental arithmetic; using rote memorisation of anchor-dates). All questions were presented on a 1-5 Likert scale (*strongly disagree, disagree, neither agree nor disagree*, *agree, strongly agree*). An additional question (Q5) was to ensure participants were paying attention and two final optional questions provided text boxes to enable participants to add further information if they wished (Q6 and Q10; not analysed). Once this strategy questionnaire was complete, participants saw a final screen thanking them for their time. A last set of revision materials were then automatically emailed to participants containing an extra rule that had not been presented during our study (Supplementary Materials C) and this was included if the participant wished to expand their knowledge further.

**Results**

Of our 35 participants, data from four were excluded from the Tutorial 1 analysis and data from two were excluded from the Tutorial 2 analysis because they used incorrect response buttons (i.e., the right-hand numeric keypad rather than the number keys). Data from a further six participants were excluded (one from Tutorial 1, four from Tutorial 2, and one from the Final Test Session) due to scoring below chance level indicating they had not engaged with the calendar rules presented during our tests. This resulted in a total of 30 participants being included in Tutorial 1, 29 participants included in Tutorial 2, and 34 participants included in the Final Test Session. To maximise analysable data, exclusions were performed on a session by session basis, (e.g., subjects were removed from tutorials if they fell below chance but could still be included in later sessions) and this was to recognise that subjects' performance can drop temporarily but get back on track later during the course of the 3-week study. We took additional precautions to ensure that our results were not driven by participant drop-out rates between groups (e.g., low-scoring synaesthetes or high scoring controls; see Footnote[2]). All confidence intervals are reported as unstandardized throughout the manuscript.

**Pre-session (week 1)**

*Mental arithmetic test*

An independent-samples t-test showed no significant differences in accuracy scores between synaesthetes (M = 96.92%, SE = 1.06) and controls (M = 94.09%, SE = 2.29), $t(33) = .91$, $p = .369$, $d = .35$, 95% CI [-3.50, 9.16]. Additionally, no significant differences were found in response times (RT's) between synaesthetes (M = 7650, SE = 656) and controls (M = 6993, SE = 492), $t(33) = .80$, $p = .427$, $d = .28$, 95% CI [-1004, 2316].

*Cognitive styles questionnaire*

Figure 3 shows all factors of the SCSQ. We conducted a 2x6 ANOVA contrasting group (synaesthetes vs. controls) and the individual factors of the SCSQ. There was no significant main effect of group ($F(1,33) = 2.91$, $p = .097$, $\eta p2 = .08$). A significant main effect of factor was found ($F(5,156) = 18.96$, $p<.001$, $\eta p2 = .37$) as well as an interaction between group and factor ($F(5,165) = 2.69$, $p = .023$, $\eta p2 = .08$). Detailed explorations with Bonferroni correction showed that synaesthetes scored significantly higher on the imagery ability factor

[2] We found that 63.88% of synaesthetes (n = 23) and 54.16% of controls (n = 26) dropped-out from our study between Tutorial 1 and the final Main Test and a chi square test of association did not show this to be a significant difference ($\chi2(2) = .80$, p = .37. To ensure that these drop-outs did not account for any of our effects between groups in our tests we analysed participant's calendar calculation performance across Tutorials for the drop-outs. Firstly, we found no significant differences between groups in their overall performance for Spot Quiz (Rule 1) when looking only at those participants (synaesthetes, n = 15; controls n = 16) who dropped-out after Tutorial 1 (t(29) = .41, p = .124). In addition, we found no significant differences between groups (synaesthetes, n = 8; controls n = 10) in their overall performance for the same Spot Quiz when looking only at those participants who dropped-out after Tutorial 2 (t(16) = -1.13, p = .277). This suggests that our results were not influenced by participants in either group dropping out as a result of their performance (e.g., high-scoring synaesthetes or low-scoring controls). If anything, there was a tendency to lose low-performing controls given that Tutorial 1 drop-out-controls (n = 16) performed worse on Spot Quiz (Rule 1) than controls who stayed in (n = 32; t(46) = -1.97, p = .054, d = .59) while no such trend was found for synaesthetes on this same Spot Quiz who dropped out from the same session (n = 15) compared to synaesthetes who did not drop out (n = 21) (t(34) = .49, p = .629, d = .17) This conservative pattern would leave behind the best-performing controls, who were nonetheless out-performed by synaesthetes in our final Main Test analyses (see below).

($p$ = .009, 95% CI [.17, 1.05]) and a trend for synaesthetes to score lower than controls on global bias ($p$ = .053, 95% CI [-.95, .01]), all other factors were non-significant (all $p$>.05).

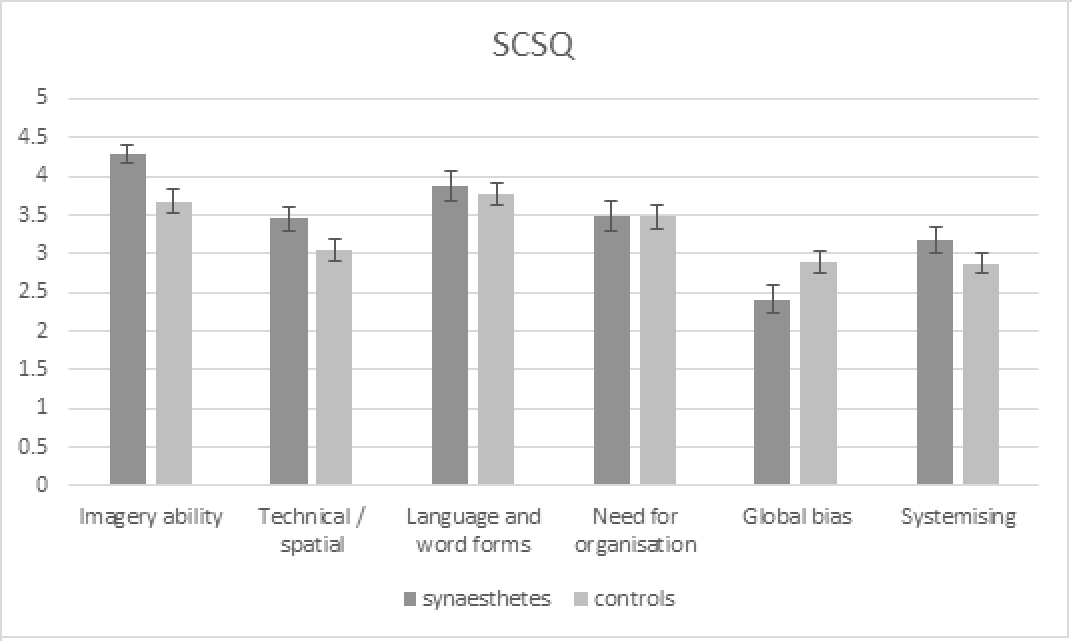


Figure 3. The profile of SCSQ scores by group and factor. Error bars show SEM.

**Spot Quiz (Rule 1) - the matching-month priming test (across weeks 1, 2, & 3)**

Response times for this spot quiz (and all subsequent calendar calculation tests) were calculated based only on correct trials. Responses were generally slow (around 10 seconds) so outlier RTs below 500 msec were discarded, as were those more than 1.96 standard deviations above the overall RT group mean.

We conducted a 2x2x3 mixed ANOVA to examine the effect of group (synaesthetes vs. controls; Figure 4a & 4c) and question type (primed vs. unprimed; Figure 4b & 4d) on accuracy scores and RT's for the *Spot Quiz: matching-month priming* test across all three repetitions (i.e., weeks 1-3). Since our mixed ANOVA analysis only takes into consideration those participants who completed all sections of our study (and some participants dropped-out after Tutorial 1) we also include an additional analysis looking at all participants who took part in Tutorial 1 (see Footnote[3]) showing that the pattern of results is not affected by dropout.

*Accuracy*

There was a significant main effect of question type ($F(1,28) = 15.22$, $p<.001$, $\eta p2 = .35$). Figure 4b shows that, overall, higher scores were produced for the primed questions (M = 82.07%, SE = 3.11) compared to the unprimed questions (M = 75.53%, SE = 4.01), and this is as we had hypothesised (given that primed questions would be easier if participants were faithfully following our instructions). There was a trend for an effect of week ($F(2,56) = 3.22$, $p = .074$, $\eta p2 = .10$) such that scores improved for the matching-month priming test Spot Quiz in each subsequent week (week 1: M = 73.68%, SE = 5.48; week 2: M = 80.16%, SE = 3.11; week 3: M = 82.55%, SE = 3.14). There was no main effect of group ($F(1,28) = 1.02$, $p = .307$, $\eta p2 = .04$) and there was no interaction between group and question type ($F(1,28) = 2.40$, $p = .133$, $\eta p2 = .08$) and no interaction between group and week ($F(2,56) = .09$, $p = .917$, $\eta p2 = .003$). Finally, there was no interaction between question type and week ($F(2,56) = 1.04$, $p = .446$, $\eta p2 = .04$) and no interaction between question type, week, and group ($F(2,56) = .82$, $p = .446$, $\eta p2 = .03$).

In summary, there was a trend for all participants to become more accurate across weeks, and they were all more accurate on those questions we expected to be easier (‘primed’ questions).

[3] If we repeat our matching-month priming test analysis including all participants who took part in Tutorial 1 (30 synaesthetes, 39 controls) our pattern of results remains largely the same. Here, no significant differences were found between synaesthetes and controls on any of the measures. No significant difference was found between groups in accuracy scores for the primed questions ($F(1,68) = .08$, $p = .733$) or the unprimed questions ($F(1,68) = .24$, $p = .629$). Similarly, no significant group differences were found in RT’s for the primed questions ($F(1,68) = 1.10$, $p = .297$) or the unprimed questions ($F(1,68) = 1.24$, $p = .269$).

*Response times*

There was a significant main effect of question type ($F(1,26) = 129.58$, $p<.001$, $\eta p2 = .83$) Figure 4d shows that, overall, faster RT's were produced for the primed questions (M = 8558, SE = 418) compared to the unprimed questions (M = 10964, SE = 529). There was a main effect of week ($F(2,52) = 31.18$, $p<.001$, $\eta p2 = .55$) and post-hoc comparisons revealed significant differences between week 1 and week 2 ($p = .025$), week 1 and week 3 ($p<.001$), and week 2 and week 3 ($p<.001$). Figure 4c shows that, overall, RT's reduced in each subsequent week (week 1: M = 11606, SE = 603; week 2: M = 10075, SE = 602; week 3: M = 7601, SE = 431). No main effect of group was found ($F(1,26) = 1.70$, $p = .204$ $\eta p2 = .06$) and there was no interaction between group and question type ($F(1,26) = .15$, $p = .701$, $\eta p2 = .01$). There was an interaction between group and week ($F(2,52) = 5.70$, $p = .006$, $\eta p2 = .18$) with post-hoc comparisons revealing significantly longer RT's for synaesthetes (M = 13142, SE = 966) compared to controls (M = 10070, SE = 720) in week 1 ($p = .030$) but not in week 2 ($p = .455$) or week 3 ($p = .969$) – see Figure 4c.

Finally, there was an interaction between question type and week ($F(2,52) = 13.80$, $p<.001$, $\eta p2 = .35$). This reveals that both the primed and unprimed questions improved over time (i.e., faster RT's), while improvements for the unprimed questions was delayed by one week. Hence Figure 4d shows a steep improvement in RT's for the primed question type between week 1 and week 2 ($p = .001$), and a steep improvement in RT's for the unprimed question type between week 2 and week 3 ($p<.001$). There was no interaction between question type, week, and group ($F(2,52) = .11$, $p = .871$, $\eta p2 = .004$).

In summary, all participants became faster across weeks, and they were faster on those questions we expected to be easier ('primed' questions). These 'primed' questions also showed an early improvement during weeks 1 and 2, while ‘unprimed’ questions saw their greatest improvement during weeks 2 and 3. Finally, synaesthetes were slower than controls during the first week of questions.

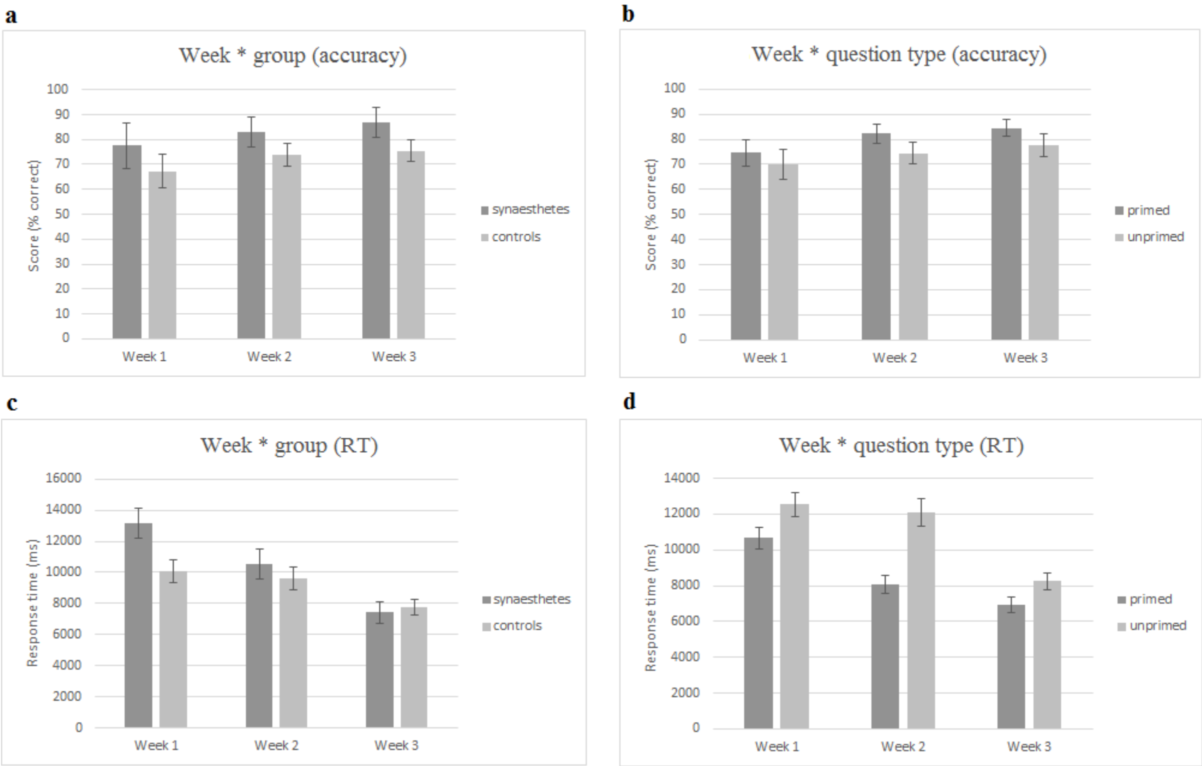


Figure 4. Distributions of participants’ overall performance across all three weeks. 4a shows accuracy scores between groups. 4b shows accuracy scores between the primed and unprimed question types. 4c shows response times between groups. 4d shows response times between the primed and unprimed question types. Error bars show SEM.

**Spot Quiz (Rules 2-6) – cross years test (across weeks 2 & 3)**

We conducted a 2x2 repeated measures ANOVA to examine the effect of group (synaesthetes vs. controls) on accuracy scores and RT’s for the *Spot Quiz: cross-years test* across week 2 and week 3 (Figure 5).

*Accuracy & response times*

For accuracy, there was no main effect of week ($F(1,24) = .99$, $p = .755$, $\eta p2 = .004$) and no main effect of group ($F(1,24) = .60$, $p = .445$, $\eta p2 = .03$). There was also no interaction between week and group ($F(1,24) = .03$, $p = .868$, $\eta p2 = .001$). For RTs, a main effect of week was found ($F(1,24) = 11.94$, $p = .002$, $\eta p2 = .33$) such that RTs were faster in week 3 (M = 13134, SE = 745) compared to week 2 (M = 15727, SE = 870; see Figure 5). There was no main effect of group ($F(1,24) = .07$, $p = .795$, $\eta p2 = .003$) and no interaction between group and week ($F(1,24) = .33$, $p = .573$, $\eta p2 = .01$).

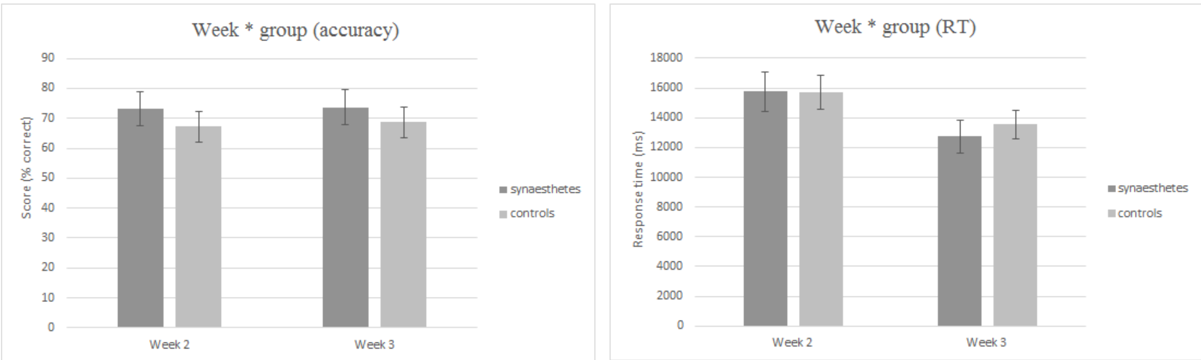


Figure 5. Participants' accuracy and RT's during the cross-years test for week 2 and week 3. Error bars show SEM.

In summary, all participants performed similarly in becoming faster between weeks 2 and 3, but there were no differences across groups.

**Main Test (week 3)**

*Accuracy and response times*

Figure 6 shows violin plots of accuracy and RT's across groups (13 synaesthetes vs. 21 controls). Distributions were found to be non-normal for both synaesthetes and controls therefore we performed an independent-samples t-test with bootstrapping (BCa based on 1000 samples) for both accuracy scores (equal variances not assumed) and RT (equal variances assumed). Using this approach, synaesthetes (M = 84.23%, SE = 3.87, range = 47.50 – 97.50) were found to have overall higher accuracy scores compared to controls (M = 67.98%, SE = 5.99, range = 10.00 – 97.50) and this difference was found to be significant (t(31.12) = 2.28, *p* = .032, *d* = .75, 95% CI [2.54, 29.13]). For RT's, similar means can be observed for both synaesthetes (M = 11405, SE = 904, range = 6624 - 16360) and controls (M = 10417, SE = 871, range = 5027 - 20105) and this was not found to be a significant difference (t(32) = .75, *p* = .435, *d* = .27, 95% CI [-1591, 3328]). Although RT's had already been cleaned by removing slow outliers prior to data analysis, we further examined RT's by removing two additional slow controls (RT's = 20105 and 17121 respectively). Even after removing these two controls we still found no difference in RT's between groups (t(24.68) = 1.62, *p* = .118, *d* = .59, 95% CI [-502, 4205]).

Given that we were only able to objectively verify eight of our 13 synaesthetes, we repeated the above analysis and found that our pattern of results remains the same when the five unverified synaesthetes are excluded from the data. Here, a t-test (equal variances not assumed) with bootstrapping (BCa based on 1000 samples) revealed that the eight synaesthetes (M = 91.25%, SE = 1.89, range = 80.00 – 97.50) still showed superior performance on the Main Test compared to controls (M = 67.98%, SE = 5.99, range = 10.00 – 97.50) and this difference was still significant (t(23.51) = 3.70, *p* = .008, *d* = 1.18, 95% CI [11.82, 33.84]). Reaction times were again observed to be equivalent between synaesthetes (M = 10614, SE = 1167, range = 6624 - 16360) and controls (M = 10417, SE = 871, range = 5027 - 20105), in a t-test (equal variances assumed) with bootstrapping (BCa based on 1000 samples; t(27) = .12, *p* = .889, *d* = .05, 95% CI [-2545, 2924]).

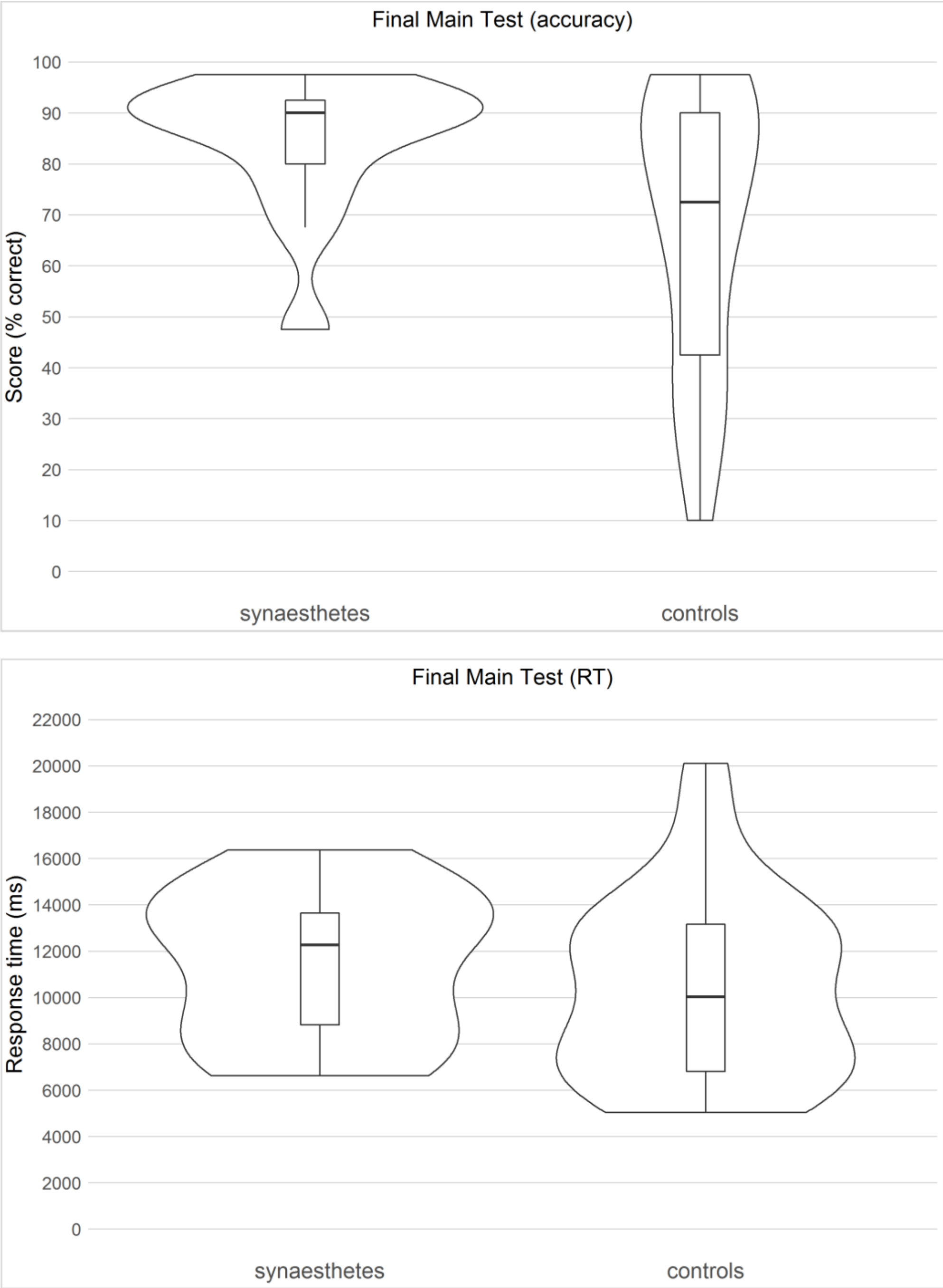


Figure 6. Violin plot showing participants' accuracy (top) and RT's (bottom) during the final Main Test of week 3 involving 40 random dates between the years 2011 and 2017. The plot displays a smoothed density distribution for each group across the full range of scores. A box-plot also shows the median (horizontal line within the box), interquartile range (lower and upper bounds of the box), and the smallest and largest values within 1.5* the interquartile range (whiskers of the box).

*Final Main Test speed-accuracy trade-off*

We further explored the speed-accuracy trade-off for the final Main Test, given the numerical difference in response times between groups (despite this difference not being statistically significant). Figure 7 shows participant (synaesthetes vs. controls) accuracies on the final Main Test plotted against RT's. The accuracy advantage of synaesthetes is apparent even at the earliest time points which is inconsistent with a speed-accuracy trade-off and consistent with a genuine difference in ability. In addition, we found no correlation (all groups combined) between response time and accuracy ($r(34) = .08$, $p = .637$) which further supports a lack of a speed-accuracy trade-off.

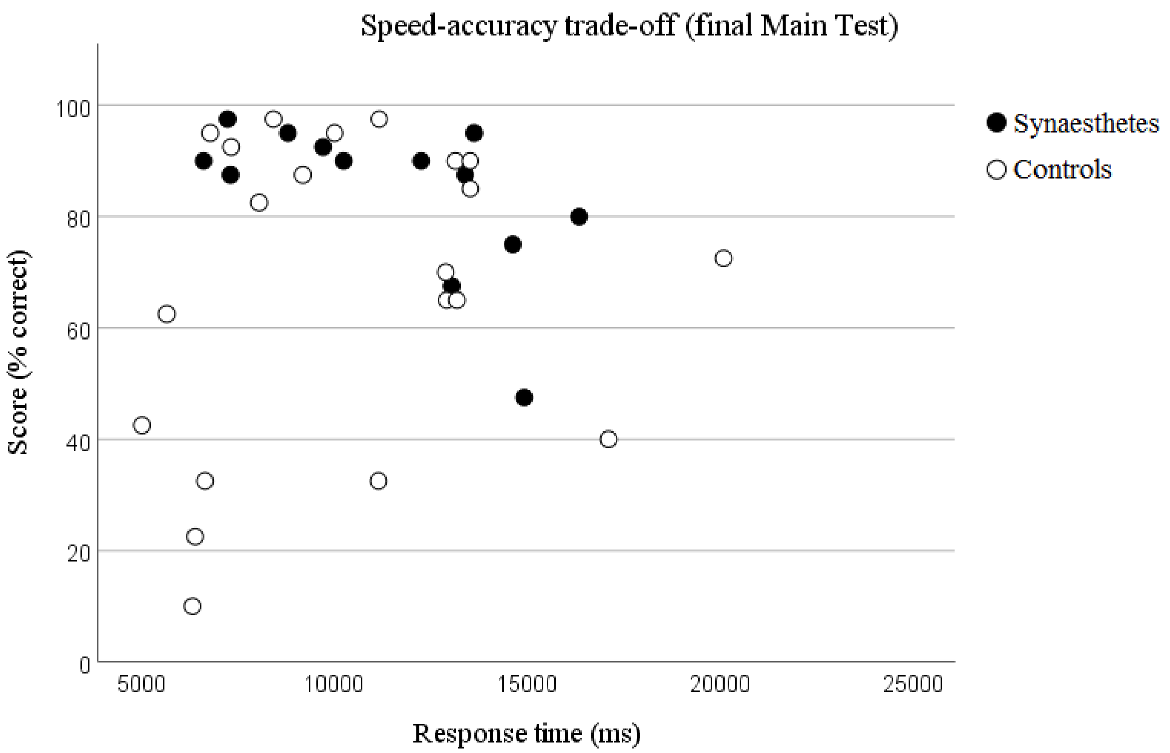


Figure 7. Scatter plot of participants (synaesthetes vs. controls) accuracy and RT's on the final Main Test.

From the above analyses we have seen that synaesthetes out-perform non-synaesthete controls in our Main Test of calendar calculation. There was no evidence of faster learning across sessions, or of a priori advantages for synaesthetes from the start. However, in our Main Test synaesthetes were more accurate than controls, and no faster or slower. One interpretation of our findings is that synaesthetes are better able to acquire calendar calculating skills as a result of their unusual internal projections of time. An alternative hypothesis is that our study shows a more prosaic effect: that synaesthetes performed better because they completed an earlier Spot Quiz more slowly and so perhaps more carefully. This relates to our finding in the *Spot Quiz: matching-month priming test* of a session x group interaction: in Week 1 synaesthetes were significantly slower than controls, despite equivalent accuracy. We therefore tested this alternative interpretation by returning to our data to remove synaesthetes (N = 1) who were particularly slow participants in Week 1, or controls who were particularly fast (N = 1). This allowed us to balance this Spot Quiz for RT in week 1, but we still found a trend for synaesthetes superiority in the Main Test in week 3 ($p$ = .064, $d$ = .65). In other words, synaesthetes were better not simply because some were slower in week 1.

*Practice between Tutorials*

We additionally looked at the amount of practice reported by participants between Tutorials to investigate whether this might account for any of our above group differences. The average amount of independent practice reported by both groups was generally low (less than 3 minutes per day). An independent-samples t-test determined no significant difference in the amount of practice reported between Tutorial 1 and Tutorial 2 for synaesthetes (M = 1.46, SD = 1.90) and controls (M = 2.00, SD = 4.05), $t(33) = -.45$, $p = .656$. Similarly, there was no significant difference in the amount of practice reported between Tutorial 2 and Tutorial 3 for synaesthetes (M = 3.91, SD = 8.89) and controls (M = 1.57, SD = 2.60), $t(30) = 1.13$, $p = .267$. We note that one synaesthete was an outlier who reported much more practice compared to other participants (more than 10 times as much) but this did not account for our findings: even without this participant, synaesthetes still out-performed controls in accuracy for our final Main Test ($t(30.90) = 2.27$, $p = .030$, $d = .76$) without a time penalty ($t(31) = .43$, $p = .16$, $d = .16$). In other words, practice effects between synaesthetes and controls did not account for our findings in the final Main Test.

*Strategy Questionnaire*

Figure 8 shows the individual questions of the strategy questionnaire that relate specifically to the use of strategies (Q1, Q2, Q3, Q4) during the calculation of dates. Scores above 3 were taken as an indication that the participant was using some type of strategy since this corresponds to the answers “agree” and “strongly agree”. Controls indicated the use of all strategies apart from mental imagery (i.e., using the on-screen timeline, mental arithmetic, and rote memorisation) while synaesthetes indicated use of all strategies apart from mental arithmetic. We conducted a 2x4 ANOVA contrasting group (synaesthetes vs. controls) and the individual questions of the strategy questionnaire. There was no significant main effect of group ($F(1,28) = .60$, $p = .447$, $\eta p2 = .02$) but there was a significant main effect of question ($F(3,84) = 3.20$, $p = .027$, $\eta p2 = .10$), although more conservative pairwise comparisons with Bonferroni correction did not reveal any significant differences between the questions. A trend was found for an interaction between group and factor ($F(3,84) = 2.30$, $p = .08$, $\eta p2 = .08$). Given this trend, we report the Bonferroni corrected post-hoc comparisons for the individual questions. These reveal that controls used mental arithmetic as a strategy significantly more often than synaesthetes ($p = .015$, $d = .91$, 95% CI [-2.41, -.28]) while synaesthetes used mental imagery more often than controls (as a trend, $p$ = .059, $d$ = .79, 95% CI [-.05, 2.27]).

Given the above trend for synaesthetes to score more highly than controls on the imagery ability factor of the SCSQ, we investigated whether mental imagery in general might contribute to calendar calculation performance (rather than synaesthesia itself). However, a correlation revealed no association between imagery ability scores from the SCSQ and accuracy scores on the final Main Test for synaesthetes ($r$(13) = .19, p = .546, 95% CI [-.41, .67]), controls ($r$(21) = -.004, p = .985, 95% CI [-.43, .43]), or when both groups were combined ($r$(34) = .17, p = .352, 95% CI [-.18, .48]). Similarly, a correlation revealed no association between imagery ability scores from the SCSQ and RT on the final Main Test for synaesthetes ($r$(13) = .03, p = .921, 95% CI [-.529, .572]), controls ($r$(21) = .27, p = .230, 95% CI [-.178, .631]), or when both groups were combined ($r$(34) = .25, p = .152, 95% CI [-.10, .54]).

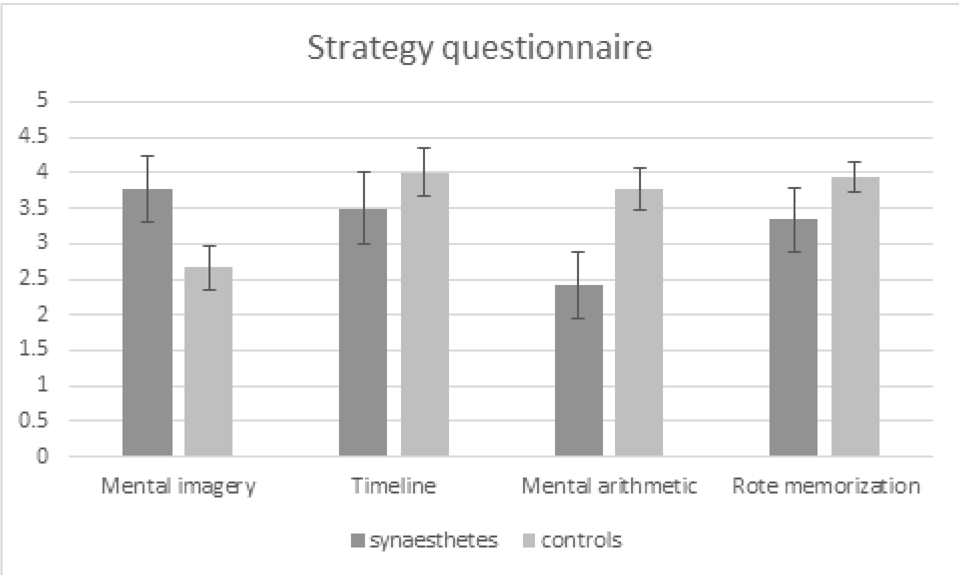

Figure 8. Group differences on the use of individual strategies during the calendar calculation sessions. Participants rated their use of strategies on a 1-5 Likert scale (*strongly disagree, disagree, neither agree nor disagree, agree, strongly agree*). Error bars show SEM.

**Discussion**

In our study we taught the skill of calendar calculation over three weeks to a group of sequence-space synaesthetes and a group of controls without synaesthesia. Sequence-space synaesthetes have strong mental impressions of time mapped into patterns in space. Our key finding was that synaesthetes better acquired the skill of calendar calculation because they were more accurate in our Main Test, without being any slower than controls. We also found that synaesthetes *had* been slower in an earlier Spot Quiz in week 1 of their testing, but that their superiority in the Main Test remained even when this RT difference was controlled for.

The purpose of our study was to investigate whether sequence-space synaesthesia might act as a scaffold to learning the savant skill of calendar calculation. Our motivation came from evidence that synaesthetic-like mental imagery appears to aid calendar calculation skills in anecdotal case reports (Howe & Smith, 1988), that sequence-space synaesthetes have special abilities in time/date-related tasks (Mann, Korzenko, Carriere, & Dixon, 2009; Simner et al., 2009), and that synaesthesia is found at higher rates in savant populations more generally (Hughes et al., 2017). We were also motivated by a theoretical account that links synaesthesia to savant skills directly. This theory suggests that savant skills such as calendar calculation are likely to arise if ASC individuals also happen to have synaesthesia (e.g., Simner et al., 2009). We also considered several additional accounts for the development of calendar calculation skills that have so far lacked consensus. These specify that calendar calculation skills might rely on the use of visual imagery, mental arithmetic, rote memorisation, and knowledge of calendrical patters/regularities. We tested these by also including a Strategy Questionnaire, and a Cognitive Styles questionnaire (see below).

Starting with group differences, we found that sequence-space synaesthetes outperformed controls in our final Main Test of calendar calculation in week 3, even without any differences between groups in response times and no differences in the amount of practice spent between sessions. But although synaesthetes were better in our final test they did not show advantages from the start. We did not observe any significant differences in accuracy across groups for any of our Spot Quizzes, introduced from week 1, and repeated across weeks. The fact that synaesthetes did not show advantages from the start suggests that sequence-space synaesthesia does not immediately elevate an individuals' calendar calculation skill levels in tasks that take time to acquire but instead affords advantages after initial learning has taken place. It could also be that advantages occurred after synaesthetes had the opportunity to learn how to incorporate their synaesthetic spatial forms into helping them perform calendar calculation, and there is at least evidence for this in our strategy questionnaire described below. Although our results indicate advantages for synaesthetes at the group level in our final Main Test, it is also important to consider alternative explanations. For instance, rather than concluding that high performance is indicative of a synaesthete advantage it could simply be that some of our controls particularly struggled with the test resulting in a low motivation to perform well and this would account for low scoring controls who also had fast response times. Having said this we also observed synaesthetes with similarly fast response times who nevertheless scored at the highest accuracy ranges and we interpret this as a genuine difference in ability rather than a speed-accuracy trade off.

It was important that synaesthetes and controls were found to have equivalent mental arithmetic ability in our pre-session test because mental arithmetic has been previously suggested as a requirement when calendar calculating (Cowan & Frith, 2009; Ho, Tsang, & Ho, 1991; Menon et al., 2000). We did however find differences in the use of mental arithmetic between synaesthetes and controls in our strategy questionnaire, as well as other differences in their cognitive profiles more widely. Whereas controls reported the use of mental arithmetic significantly more often than synaesthetes, there was a trend for synaesthetes to use mental imagery more than controls. We suggest this imagery is likely to be their synaesthetic imagery of time. All our synaesthete participants reported experiencing spatial forms for both days and months (as well as numbers) and the question remains as to exactly how these representations might facilitate calendar calculation skills. It could be that synaesthetes' spatial forms allow them to more accurately locate days of the week using their synaesthetic timelines. Alternatively, synaesthetic spatial forms might allow the generation of 'anchor dates' within months (which were used during our study as one technique to facilitate the location of nearby dates).

This use of imagery also fits with findings from our second questionnaire measure. Synaesthetes scored significantly higher than controls on the imagery ability factor of the SCSQ, which supports previous findings of enhanced imagery in synaesthetes (Barnett & Newell, 2008; Havlik et al., 2015; Price, 2009; Spiller & Jansari, 2008; Spiller, Jonas, Simner, & Jansari, 2015). It might be suggested that superior imagery in general (rather than synaesthesia in particular) could account synaesthetes' superior calendar calculation skills. However our analyses did not find any association between imagery ability per se and accuracy scores or RT's in the final Main Test. This suggests that it is synaesthesia itself that produces benefits in calendar calculation skill acquisition. Nevertheless, our small sample size and wide CI's prevent us from ruling out the possibility of a link between our findings and imagery ability in general and so replications of our findings are encouraged. We also found a trend for synaesthetes to score lower compared to controls on the global bias factor (i.e., synaesthetes self-reported more local bias). Local bias is a feature commonly associated with autism and has been theorised to facilitate the development of savant skills (Bouvet et al., 2014; Mottron, Dawson, & Soulieres, 2009; Mottron, Dawson, Soulières, Hubert, & Burack, 2006) and therefore this might indeed provide advantages when learning to calendar calculate.

As well as finding group differences in our strategy questionnaire, we also found a multifaceted strategical approach to calendar calculating: Controls, on average, indicated the use of all strategies apart from mental imagery (i.e., using the on-screen timeline, mental arithmetic, and rote memorisation) while synaesthetes, on average, indicated use of all strategies apart from mental arithmetic. This multifaceted approach also fits with previous explanations of calendar calculation as relying on either mental imagery (Howe & Smith, 1988; Roberts, 1945), mental arithmetic (Cowan & Frith, 2009; Minati & Sigala, 2013) and rote memorisation (Boddaert et al., 2005; Heavey et al., 1999). This also supports previous evidence for the influence of individual learning histories on brain activation patterns in calendar calculators (Fehr et al., 2011) and the development of neural networks involved in complex mental processes (Fehr, 2013). Calendar-calculators also have to have knowledge of calendar patterns or rules (Cowan, Stainthorp, Kapnogianni, & Anastasiou, 2004) and this was the knowledge imparted during our tutorials.

Moving away from synaesthesia our findings also relate more generally to the calendar calculation literature. Calendar calculation as well as other savant abilities have been somewhat shrouded in mystery and are considered well beyond the capabilities of most people. However, Rieznik, Lebedev, and Sigman (2017) recently commented that this presumption about the nature of so-called extraordinary skills is fundamentally flawed because similar feats can be achieved by most people using common techniques. Our data supports the view of Rieznik et al. (2017), although we qualify it by saying that the ability to learn these skills, and the motivation for doing so, may differ in important ways. In our study we show that although calendar calculation is a very rare skill it is surprisingly easy to acquire.

We employed a novel experimental methodology to train individuals how to calendar calculate by teaching them a collection of rules, patterns, and regularities of the calendar. After around one cumulative hour of training (spanning two weeks with a final test in the third week), participants could calculate dates from a 7-year range (2,555 dates) with around 80% accuracy and in about 10-12 seconds. In principle, this could be extended to any year because the calendrical patterns repeat beyond the dates that we used in our study. We also included a test of whether our participants were internalising the rules we taught. We found, as hypothesised, that our 'primed' questions were more easily answered than 'unprimed' questions, and this shows directly that participants were using one of the rules we had taught them (the 'matching month' rule). Previous studies also show that some calendrical savants may make use of calendar rules like the ones presented in our study (Hermelin & O'connor, 1986; O'Connor, Cowan, & Samella, 2000). In fact, the performance of our test participants coincides with previous accounts of savant performance at around 80% accuracy (Cowan et al., 2004; Hill, 1975). Having said this, it is noted that some savants have been shown to achieve extremely high calendar calculation accuracy (e.g., 97%) combined with very fast reaction times (e.g., 1.53 seconds) (O'Connor et al., 2000) reflecting lifelong idiosyncratic learning histories over much longer time periods than the current study. We suggest that future scientific investigations could benefit from the consideration of the techniques used to attain expert memory performance as this could prove beneficial in our understanding of the cognitive mechanisms that allow extraordinary mental skills to flourish.

One limitation of the current study is that a high proportion of participants dropped-out between sessions. This is because our study required a substantial commitment from the participant to learn the rules of calendar calculation and to return for subsequent training sessions. We acknowledge that this high drop-out rate reduces our statistical power since many participants did not make it to the end of the final testing session. Having said this, our analysis of Tutorial 1 produced the same pattern of results both when looking only at those participants who completed our entire study (i.e., with a reduced N) and when analysing the larger cohort of participants who dropped-out in later sessions. Nevertheless, our low participant numbers and subsequent wide effect sizes make replication of our results a necessity.

An additional limitation is that it could be suggested that the online nature of the current study cannot rule-out the possibility that participants were cheating. However our testing protocol limited this possibility as much as possible. For instance, to avoid participants looking up answers our study prevented participants from minimizing the screen during testing (i.e., to look up answers elsewhere). It is also worthwhile to point out that our 'priming effect' also rejects the possibility of participant cheating since this effect would not be so evident if participants used external resources to look up the date answers. Nevertheless, online experiments like the current study should consider carefully the prospect that participants' behaviours cannot be so easily controlled. Finally, there is no evidence to suggest that synaesthetes were merely more motivated: they did not report more motivation/interest in calendar calculation in the strategy questionnaire (but did report a different learning style); they did not show evidence of faster learning of the rules during the learning phase of the study (but did show better long-term retention as revealed in the final Main Test); and they were no more likely to drop-out.

In conclusion, our study demonstrates for the first time that calendar calculation skills can easily be acquired by most individuals using a structured rule-based approach. We found that sequence-space synaesthetes performed better than controls during our final test of calendar calculation, but they did not demonstrate better performance from the start. We suggest that cognitive benefits afforded through synaesthesia may act as a scaffold to the performance of calendar calculation skills after initial learning has taken place. Our results support previous theories linking synaesthesia and savant syndrome (e.g., Baron-Cohen et al., 2007; Simner et al., 2009) as well as evidence that sequence-space synaesthesia is associated with advantages in relevant domains (Mann et al., 2009; Simner et al., 2009). We add however that these benefits are less immediate with skills that take time and effort to acquire. We also present evidence to show that individuals in general acquire calendar calculation skills using a multifaceted approach based on strategies relating to mental arithmetic and rote memorisation as well as novel strategies that are available at the time (e.g., using a timeline on a computer screen to count days of the week). The presence of particular cognitive styles was also found to influence strategies (e.g., synaesthetic mental-imagery). Finally, knowledge of calendar patterns and rules acts as a catalyst in acquiring calendar calculation skills. We suggest that future studies may benefit from the consideration of techniques used by savants and memory athletes as this may be useful in informing us about the cognition of expert performers (Rieznik et al., 2017).

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*Authors' contributions*

JW was responsible for the overall direction of the research. Data were collected by JEAH and EG. JEAH, JS, JW, and EG conducted the analyses. The paper was written by JEAH, JS, JW and EG.

*Availability of data*

The datasets supporting the conclusions of this article are available via the UK Data Service.

*Competing interests*

The authors declare no competing interests.

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